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Exploring pedestrian walking through angled corridors

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Abstract

Reliability of many pedestrian modelling and simulation tools is questionable, particularly when used to simulate pedestrian walking behaviors associated with complex geometries such as angled walkways. It is uncertain that existing modeling approaches adequately capture microscopic walking behaviors associated with turning movements with regards to trajectories, speed profiles and acceleration/deceleration patterns. This paper presents preliminary results of a modelling framework that is based on comprehensive experimental data for pedestrian walking behaviors through angled corridors. Numerical simulations indicate that this model reproduces more accurate pedestrian walking behaviors through angled corridors compared to existing approaches.

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Keywords: pedestrian dynamics; turning movements; walking behaviour modelling; model calibration

1. Introduction

Large crowds can be expected at major public infrastructures not only during special events, such as religious, cultural, or sporting events, but also for daily activities, such as commuting or shopping. It is extremely important to ensure the safety of people in case of an emergency and to guarantee efficient flow of movements in day-to-day situations. In order to achieve these broad objectives, i.e. optimizing designs and management of crowds at public buildings, building designers and crowd managers can utilize pedestrian crowd simulation tools (Gwynne et al. (1999)). These modelling and simulation tools can broadly be classified as macroscopic models and microscopic

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models. While microscopic models are generally implemented through computer simulations, macroscopic models (that mainly use fundamental diagrams) can be implemented either through simulations or hand calculations. Even though the concepts and computation methods are entirely different, both methods are widely utilized to predict evacuation times under various geometrical and network settings (Rogsch et al. (2010)).

Despite popularity of these methods, there are often questions about the reliability of such tools, because they must be calibrated against reliable empirical data to ensure validity before putting them into practice. Rogsch et al. (2009) demonstrated that widely used microscopic commercial software tools, which are based on well-known social force or cellular automata models, fail to predict accurate evacuation times through simple geometries. Thus, the question arises whether those tools and models can predict accurate walking behaviors through more complex geometries such as angled or circuitous walkways. It can be argued that in order to model the realistic walking behaviors associated with complex configurations either the existing models should further be modified or new approaches be explored.

Several approaches in the literature have attempted to simulate pedestrian dynamics associated with rounding corners or angled corridors. The simplest approach is to locate intermediate destinations to change the desired direction and guide the movements through the desired path. For example, Steffen and Seyfried (2009), Höcker et al. (2010) and Zeng et al. (2011) have considered one or several intermediate destinations to plan the desired path beforehand. Chraibi et al. (2013) modelled each agent's direction around the corner through guiding lines and update rules based on the occupancy of those guiding lines by other pedestrians. Other approaches have utilized heuristic based methods (Jian et al. (2014), Kretz (2009)) and various behavioral rules (Guo and Tang (2012)) combined with existing microscopic simulations. However, it is uncertain that these approaches capture the complete situation with regards to trajectories, time-space diagrams, speed profiles and acceleration/deceleration patterns. As a result, the bottleneck effect of turning corridors might have not been represented accurately. Further, many of these models have not been calibrated or validated against empirical data related to walking through angled corridors. Therefore, further studies (empirical and theoretical) are required to understand the effect of turning angle and to model the realistic walking behaviors through angled corridors. In order to address these issues, a novel modelling framework was proposed, which is based on comprehensive experimental data for a range of turning angles, densities and desired speeds. Details of the proposed framework and initial results (i.e. model output for solo) are discussed in this paper.

The paper is structured as follows: The next section will discuss the background and the main steps of model development. This is followed by initial results obtained through numerical simulations. Lastly, conclusions and recommendations for further studies are presented.

2. Model description

2.1. Background

The proposed framework is based on a microscopic, force based, continuous model and can be combined with existing social force models. In order to build and calibrate the model, data were collected through a series of experiments with a group of people walking through corridors of different turning angles at different speeds. Details of these experiments and the data obtained can be found in Dias et al. (2014).

In force based models (Helbing et al. (2000), Shiwakoti et al. (2011)) it is assumed that when an individual is walking in a crowd, he or she is subjected to social and physical forces. Thus, the movement of an individual can be described by the following equation:

$$m_i \frac{d\vec{v}_{i,t}}{dt} = \vec{F}_{desired,i,t} + \vec{F}_{wall,i,t} + \vec{F}_{ij,t} \tag{1}$$

Where;
m_i = Mass of individual *i*
$\vec{v}_{i,t}$ = Instantaneous velocity of individual *i* at time *t*
$\vec{F}_{desired,i,t}$ = Desired force at time *t* that attracts the pedestrian *i* to the desired destination
$\vec{F}_{wall,i,t}$ = Interaction forces with walls at time *t*
$\vec{F}_{ij,t}$ = Interactions (attractions or repulsions) between pedestrian *i* and *j* at time *t*

Through the recent experimental study with a group of people, Dias et al. (2014) observed several behavioral characteristics that are specific to walking through angled paths. Those can be summarized as;

- When negotiating a turn, individuals' speed is reduced within a fixed region (say, "turning region") that can be characterized with two points; namely turn initiation point and turn completion point (Fig. 1 (a))
- There is a deceleration phase and an acceleration phase within this fixed region and the minimum speed occurs in the vicinity of the middle of the corner
- Percentage reduction in speed within this region is increased with increasing turning angle and increasing desired speed

The basic steps to develop the framework, which is based on these behavioral characteristics, are described briefly in the following sub sections.

2.2. Desired direction

As depicted in Fig. 1, through experimental data, it was observed that an individual changes his / her walking direction within the turning region gradually, in such a manner that the angular speed is a constant.

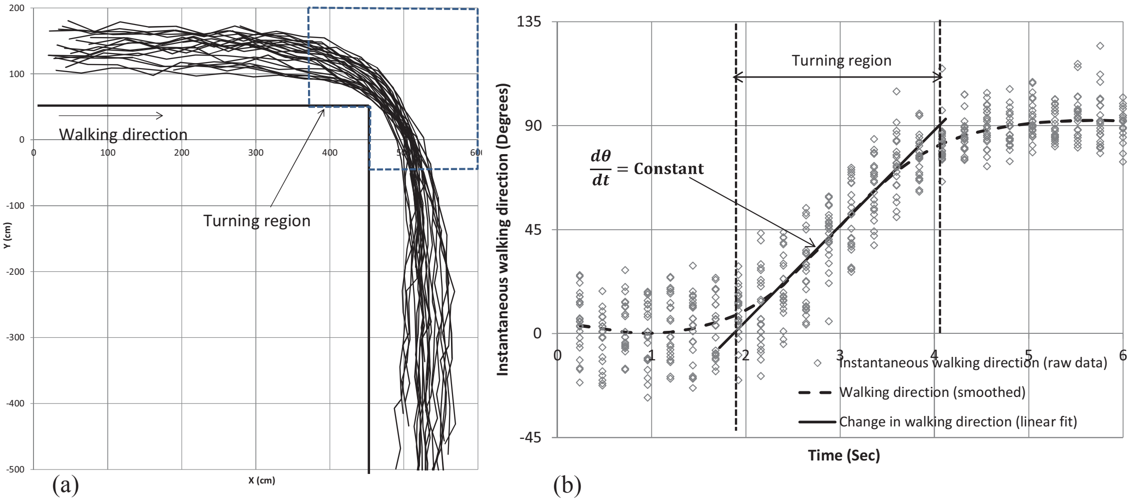


Fig. 1. (a) Individual trajectories; (b) change in walking direction with time, for 90° turning solo normal speed walking case.

In other words, when walking through an angled path, individuals' change in desired direction is gradual, not abrupt. Thus, for the constant changing in direction within the turning region:

$$\frac{d\theta}{dt} = \omega \ (constant) \tag{2}$$

Integrating within the region [*t*, *t*+*Δt*], considering that the walking direction will change from θ_t to $\theta_{t+\Delta t}$:

$$\int_{\theta_t}^{\theta_{t+\Delta t}} d\theta \ = \int_t^{t+\Delta t} \omega \ dt \tag{3}$$

This integral can be reduced to:

$$\theta_{t+\Delta t} = \theta_t + \ \omega * (\Delta t) \tag{4}$$

That is, within the turning region, the walking direction can be updated at every time step, given the value of ω, which can be empirically obtained from instantaneous walking direction versus time plots (for ex. Fig 1(b)) for all turning angles and all speed cases. Thus, within the turning region the desired velocity vector at time *t* ($\vec{V}_{des,t}$) can be given as a two dimensional vector as:

$$\vec{V}_{des,t} = \begin{pmatrix} V_{des} sin\theta_t \\ \\ V_{des} cos\theta_t \end{pmatrix} \tag{5}$$

Where;
θ_t = Instantaneous walking direction at time *t* with respect to a fixed reference line
V_{des} = Desired speed magnitude

Note that the desired direction is changed continuously until θ_t equals to θ_{max}, which is the maximum turning angle.

Then, the desired force at time *t* could be defined, similar to previous social force models, as:

$$\vec{F}_{desired,t} = m * \frac{\vec{V}_{des,t} - \vec{V}_t}{\tau} \tag{6}$$

Where;
m = Mass
$\vec{V}_t$ = Velocity at time t
τ = Relaxation time

2.3. Deceleration effect at turning

Experiment findings indicated that there is a clearly observable deceleration effect when an individual walks along an angled path. Further, it was observed that this deceleration increases with increasing speed and turning angle, because the higher the approaching speed, the larger the work that must be done to overcome the effect of inertia. Similarly, the larger the turning angle the larger the work that must be done to change the walking direction.

This deceleration effect could be modelled as a force, which is continuously changing with the changing walking direction, until the walking direction reaches the desired maximum walking direction (θ_{max}). Assuming an exponential function, the turning deceleration force within the turning region at time *t* ($\vec{F}_{turning,t}$) for an individual was formulated as:

$$\vec{F}_{turning,t} = A * exp(\delta\theta_t)\ \vec{n}_l \tag{7}$$

Where;
θ_t = Instantaneous walking direction at time *t* with respect to a fixed reference line
$\vec{n}_l$ = Unit vector that points to the opposite direction of initial desired velocity vector
A and δ are model parameters that represents the effect of approaching speed and desired turning angle

2.4. Centrifugal effect

Agents, particularly in force based microscopic simulation models, are modelled as Newtonian particles and therefore the centrifugal effect should also be considered when those agents are traversing angular or circular paths. Few previous studies related to walking on angled paths have considered centrifugal effect and modelled it as a repulsive force in the radially outward direction (for examples, see Brogan and Johnson (2003) and Guo and Tang (2012)).

As centrifugal force is proportional to the square of moving speed of the particle, $\vec{F}_{centripetal,t}$ was defined as:

$$\vec{F}_{centrifugal,t} = k * \left|\vec{V}_t\right|^2 \vec{n}_p \tag{8}$$

Where;
k = Centrifugal force constant
$\vec{n}_p$ = Unit vector that is perpendicular to the current moving direction and points outward from the walking radius

Trajectories developed from experimental data suggested that, on average, the higher the turning angle the lower the turning radius. Thus, it is logical to state that, the value of k should increase with increasing turning angle. Further, the value of k can be calibrated utilizing experimental data for a range of turning angles.

Combining these new force components, the complete model for the solo walking through an angled corridor can be written as:

$$m\frac{d\vec{v}_t}{dt} = \vec{F}_{desired,t} + \vec{F}_{wall,t} + \varphi\left(\vec{F}_{turning,t} + \vec{F}_{centrifugal,t}\right) \tag{9}$$

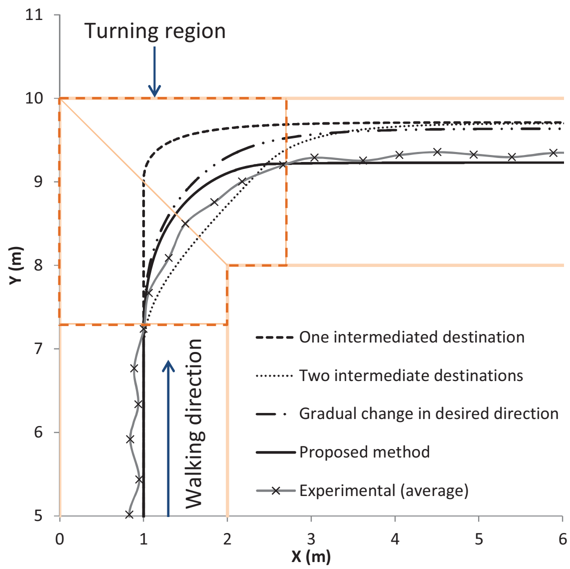
Where;
φ = 1; if the agent is within the turning region
φ = 0; otherwise

Turning deceleration and centrifugal force parameters were initially calibrated for solo, normal walking conditions, by comparing the modelled and experimental speed patterns within the turning region. Numerical simulations that were performed to evaluate the model performances are discussed in the next section.

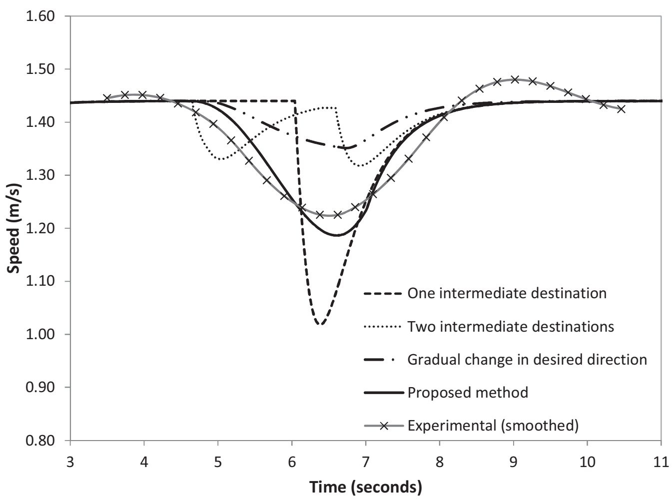
3. Numerical simulations

A 90° turning corridor was simulated under free-flow, normal walking conditions to test the framework performance over several other approaches. For this simulation, the desired speed (V_{des}) was set as 1.44 m s^{-1}, which was the free flow speed value for normal walking case estimated from experimental data (see Dias et al. (2014)). The angular speed (ω) that is required to update the walking direction (Equation 4) was estimated as 38.1 degrees sec^{-1} from the experimental instantaneous walking direction data for 90° turning case (Fig. 1(b)). Relaxation time (τ) in Equation 6 was assumed to be 0.5 seconds and the mass of an individual was assumed as 70 kg. Calibrated, A and δ (parameters in Equation 7) for 90° turning was 25 kg m s^{-2} and 0.016 (degrees)$^{-1}$ respectively. Further, the centrifugal force constant k in Equation 8 was set as 10 kg m^{-1}.

Trajectories and speed profiles (from model output) were compared with empirical data as shown in Fig. 2. This comparison suggests that the proposed approach provides more realistic trajectories and speed patterns, which are closer to corresponding average experimental values. Thus, it can be argued that the proposed framework can represent the bottleneck effect of turning angle more robustly.



(a)



(b)

Fig. 2. Comparison of (a) trajectories and; (b) speed patterns from different approaches with average experimental trajectory (for solo walking).

4. Conclusions

Complex geometries such as angled or circuitous walkways, which are common in crowd gathering places, can significantly affect microscopic walking characteristics of pedestrians. Understanding bottleneck effects due to those complex geometries and capturing those in simulation models could be very important. Through such improved understanding, the reliability of mathematical simulation models, which are being widely used in optimizing building designs and evacuation plans, could be enhanced.

A novel modelling framework was introduced in this paper to simulate pedestrian walking through angled corridors. Data collected through a series of comprehensive experiments were utilized to develop this framework. Initial numerical simulations suggest that the proposed model generates more realistic trajectories and speed profiles, thus capturing the bottleneck effect more realistically. Further, it was shown that when the proposed framework was combined with existing force based simulation models, it operates satisfactorily for average density situations. High density and extreme cases (like panic and extremely high density conditions) were not considered under this study and those were left for future tasks.

In future investigations, more complex scenarios associated with turning movements will also be considered. Further, the model will be validated with real world data for a range of densities and speed levels.

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